The Effects of Sound on the Marine Environment

Michael B. Porter
Heat, Light, and Sound Research, Inc.
3366 N. Torrey Pines Court, Suite 310
La Jolla, CA 92037
phone: (858) 457-0800 fax: (858) 228-1734 email: mikeporter@hlsresearch.com

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http://www.hlsresearch.com/

LONG-TERM GOALS

To develop novel techniques to predict the impact of sound on the marine environment and use natural sound sources (such as whale calls) to observe non-invasively both animal behavior and the marine environment.

OBJECTIVES

In recent years, there has been increasing concern about the role of man-made noise in the marine environment. To address this, ONR has supported the development of the Effects of Sound on the Marine Environment (ESME) workbench. The initial Graphical User Interface was developed by NRL using Matlab with calls to FORTRAN implementations of acoustic propagation models. The acoustic modeling tools are mostly drawn from ONR's Ocean Acoustic Library (http://oalib.hlsresearch.com), which provides the latest open source R&D models.

ESME has emerged as the likely navy standard for such modeling. Its *open source* and *peer-reviewed* approach are seen as very favorable. In addition, ESME has emphasized the need for the highest-quality results taking advantage of state-of-the-art propagation models and marine-mammal movement models. The latter leads to an 'animat' construction that simulates the motion of individual marine mammals as they move through the sound field, and respond with aversion behaviors.

The Navy needs ESME now as an operational tool. Much work is needed to rapidly bring it to that level, which is the key goal of this work.

APPROACH

The ESME team (D. Mountain, Boston University; D. Houser, Biomimetica; M. Siderius, Portland State; and HLS Research, Inc.) has now linked up with NUWC who is seen as a principal user of ESME and has been doing a large number of environmental studies for the Navy. The ESME team is working closely with NUWC to adapt the ESME workbench to their needs and to complete the integration with navy databases. NUWC uses its own tool (NEMO) for such studies and the focus of both the NUWC and ESME teams has been to merge these two tools, adopting the best of both.

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The map in Figure 1 outlines the general set of tasks as discussed in the following subsections. Within each task area we prioritize with the goal of getting a useful ESME workbench in the hands of NUWC as rapidly as possible, and then adding new features in a sequence motivated by their operational needs.

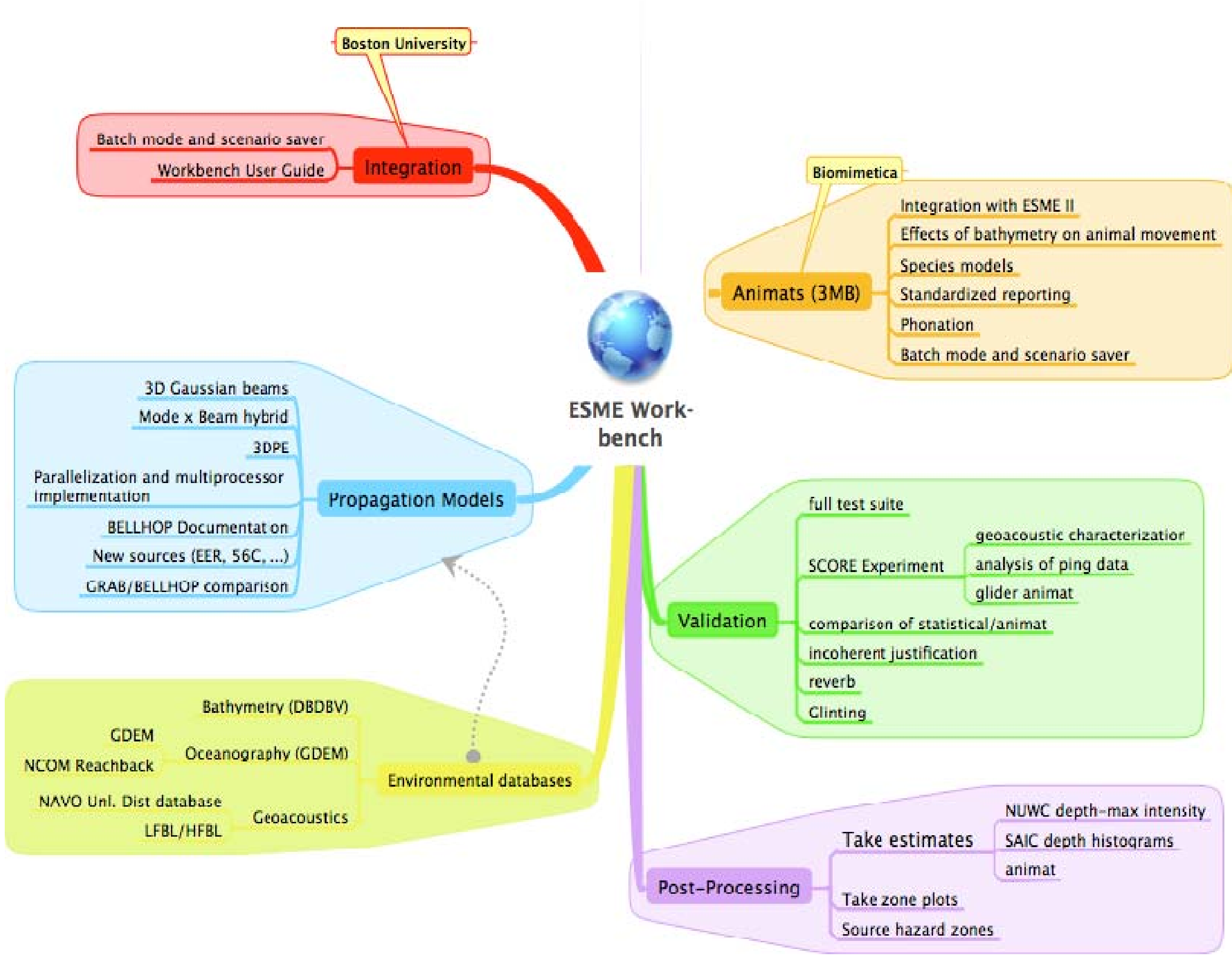

Figure 1: Components of the ESME Workbench and associated tasks. Task I: 3MB animats developed by D. Houser (not discussed in this report). Tasks II-V: Propagation models, Environmental databases, Validation and documentation, and Post-processing (HLS Research Inc.). Task VI: Integration by D. Mountain (not discussed in this report).

Task II. Propagation models

Short-term goals include investigating:

(a) The role of 'glinting', which is the high intensity sound levels due to focusing by ocean surface waves. For the ESME Workbench we use a virtual source approach to examine whether simple corrections can be made to approximate the full 3D effects of surface waves in a 2D Gaussian beam code (BELLHOP). We use also a finite-element code (COMSOL) to model these complex scattering effects.

(b) Nonlinear effects to model explosives. We are currently studying three options: 1) The NRL Nonlinear Parabolic Equation Model, 2) COMSOL, and 3) An open-source implementation of a nonlinear PE.

Long-term goals include:

(a) The treatment of 3D effects due to refraction in the Lat/Long plane caused by variation in environmental parameters in that plane (e.g. the ocean bottom topography and nonlinear internal waves (NLIW)). The approaches to this problem include 3D Gaussian beams (BELLHOP3D), 3D Parabolic Equation models, and various modal formulations.

(b) Parallelized versions of the codes for multiprocessor and multithreaded systems. This will provide High Throughput Computing with the ESME workbench, while maintaining high fidelity. We are also investigating CUDA solutions for extremely fast BELLHOP runs. CUDA is basically an architecture for using the General Purpose Graphics Processing Units standard on modern PCs for massively parallel computations. Speed-ups of 10x to 100x are commonly reported; however, the programming is more complex and not all propagation models are suitable for CUDA implementation. The GPGPUs are also packaged in separate systems where numerous GPGPUs are stacked.

Task III. Environmental databases

The ESME Workbench currently has links to localized databases related to specific simulations that were done previously. This includes AUTEC, the Stellwagen Bank off the coast of New England Site, and a site offshore North Carolina. To be generally useful, the ESME Workbench will require links to broader environmental databases including DBDB-V for bathymetry, GDEM for oceanography, and various NAVO databases for sediment properties. We will work together with Boston University to set up these linkages.

Task IV. Validation and Documentation

Validation of the ESME Workbench is a critically important issue to ensure acceptance in the broader community. The acoustic models used in the ESME Workbench are open source, peer-reviewed, and accepted tools in the ocean acoustic community. Similarly, the various databases are navy standards representing the best available science. However, further work is needed to document the tools. A key short-term effort is to provide a BELLHOP manual.

Task V. Post-Processing

While comparing different approaches to estimating takes, we have found that several displays are useful as decision aids. We are including some of these new displays in the ESME Workbench. Two important examples are the Take Zone Plots and the Source Hazard Zone Plots. The first shows geographic areas where high numbers of takes occur. The second shows geographic areas where the SONAR system causes the highest number of takes. These two displays will allow an environmental planner to consider changes in experimental plans to reduce the number of takes with minimal disruption to the experiment or exercise.

WORK COMPLETED

Ahmad Abawi has completed a theoretical analysis on the 'glinting' effect of ocean surface waves and implemented a virtual source solution through a numerical boundary integral approach. He has also installed COMSOL (general purpose finite element software) and run several simulations with simple surface wave spectra. These results are discussed below.

We have developed interfaces to the World Ocean Atlas and to NGDC bathymetry that enable the propagation tools to be used globally. Similarly, we have developed interfaces to the National Geophysical Database Center (NGDC) bathymetry at http://www.ngdc.noaa.gov/ .

RESULTS

In our previous simulations of the focusing effect of ocean surface waves, we showed that the intensity level at the focus of a curved mirror depends on frequency. This frequency dependence is linear for a singly curved mirror (e.g. a parabolic cylinder) and quadratic for a doubly curved mirror (e.g. a parabola of revolution or a paraboloid). However, the intensity at the focus of a singly curved mirror produced by an infinitely long line source has no frequency dependence. Figure 2 shows the results of our simulations using parabolic mirrors. We have reported similar results for cylindrical and spherical mirrors before and include these for completeness.

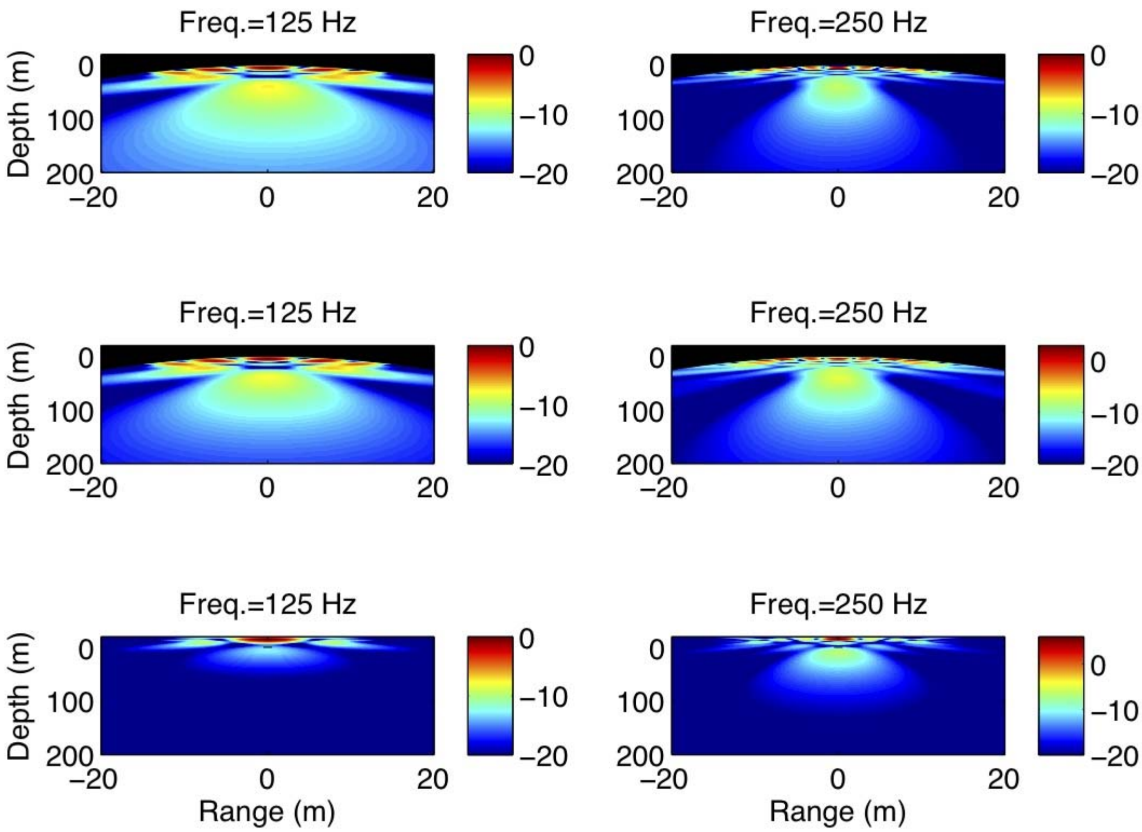

Figure 2: Frequency dependence of sound intensity at the focus produced by surface curvature. Top four panels: singly curved parabolic mirrors representing a surface curved in the horizontal direction and flat along the direction perpendicular to the page. The source is at 800 m depth, directly below the axis of the curved surface, and the focus is located at 2 m. Top row: for a line source and a 1D surface curvature, the intensity at its focus is independent of frequency. Middle row: for a point source at the same place as the previous case, the intensity at the focus is a linear function of frequency (doubling the source frequency yields ~ 3dB increase in intensity at the focus). Bottom row: for a point source ensonifying a paraboloid (doubly curved) surface with a height of 2.5 m and a base of 20 m, the intensity at its focus is a quadratic function of the frequency (doubling the source frequency yields ~ 6dB increase in intensity at the focus).

Since we reported these simulation results, we have been able to verify our findings analytically using Debye’s theory, which he developed for computing the field at the focal regions caused by the passage of light through circular apertures. Also, to show that the frequency dependence discussed above is consistent for a range of frequencies, we used the virtual source technique to compute the field intensity for frequencies ranging from 0 to 500 Hz. The results are shown in Figure 3.

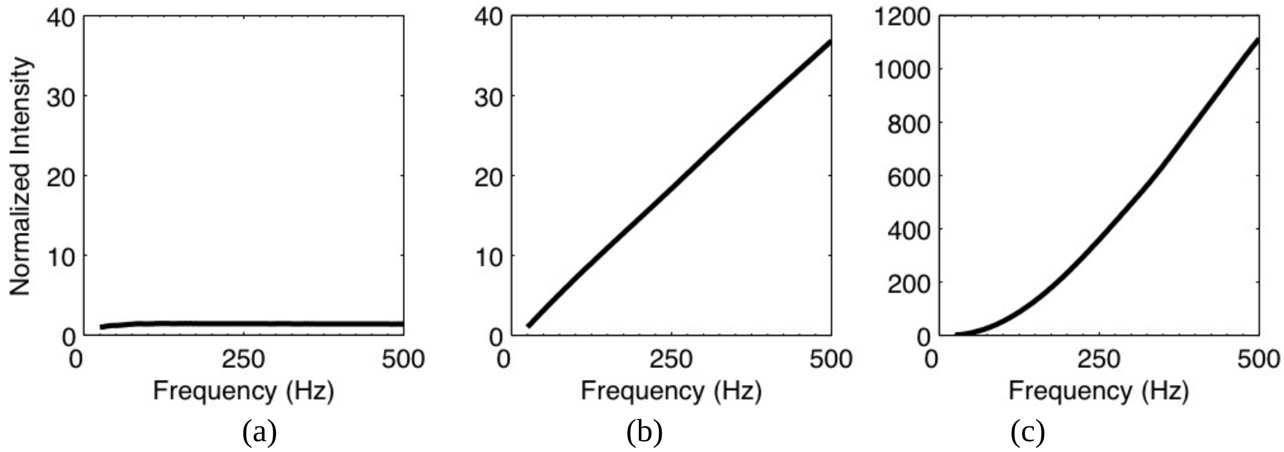

Figure 3: The frequency dependence of the intensity at the focus of a curved mirror. Frequency dependence at the focus of a singly curved mirror caused by a line source (a), or a point source (b). Frequency dependence at the focus of a doubly curved parabola (paraboloid) caused by a point source (c). There is no frequency dependence in (a), whereas the frequency dependence is linear in (b) and quadratic in (c). In these figures, the intensity is normalized by that of the smallest frequency.

To be able to examine the focusing of sound, which can result from scattering by the sea surface during a swell, we solved the wave equation in the oceanic half space using the finite element method. In this simulation we modeled the ocean surface as a singly curved (1D) sinusoid. The finite element mesh for this simulation is shown in Figure 4.

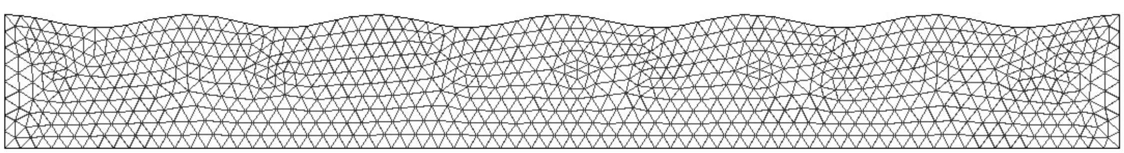

Figure 4: The finite element mesh used to simulate propagation and scattering in an oceanic half space with corrugated surface. The mesh section extends from z = 0 to 50 m depth, and x = 0 to 180 m horizontal range. A coarser mesh than the one used in the simulation is plotted to make individual triangles visible.

In this simulation, a 500 Hz source is located at ($x = 0$, $z = 20$ m). The corrugated surface is modeled to satisfy a pressure-release boundary condition and only cover the computational domain, which is 180 meters long. The computational domain is truncated by assuming that it satisfies the Sommerfeld radiation condition at the left, right and bottom boundaries. The computed acoustic intensity levels are shown in Figure 5, where in the top panel the results are for a flat surface and in the bottom panel they are for the corrugated surface shown in Figure 4. The existence high intensity spots (hot spots) due reflection from the curved boundary are clearly visible. Depending on the frequency and surface curvature, the intensity at these hot spots can be up to 6 dB higher than the average background intensity for the case of a flat surface.

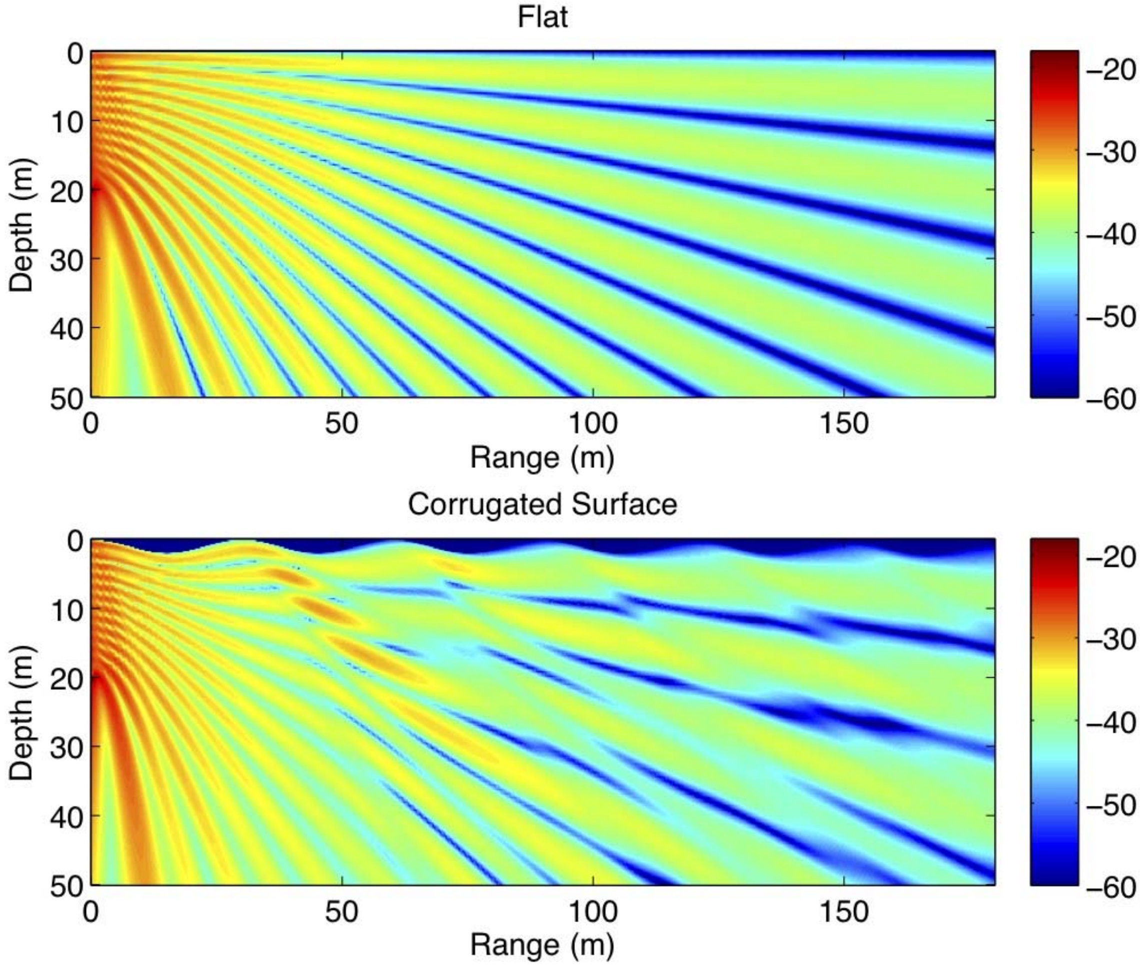

Figure 5: Intensity levels for scattering of sound from the sea surface: flat surface (top panel), corrugated surface (bottom panel). The high intensity spots due to focusing by the curved surface are clearly visible in the bottom figure. Depending on the frequency and surface curvature, the intensity at these spots can be up to 6 dB higher than the corresponding average background intensity level for a flat surface.

IMPACT/APPLICATIONS

The Navy has an urgent need for a standardized software package for modeling the impact of sound on the marine environment. Several tools have been developed and are in use; however, only ESME has been developed as an open source and peer reviewed package.

RELATED PROJECTS

The propagation models used in ESME have been largely supported by the ONR Ocean Acoustics program.